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Modeling and control strategies for energy management system in electric vehicles☆

Hitesh sharma*, Om Prakash Jaga, Sanjay Kumar Maurya

GLA University, Mathura, 281406, India

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Summary These days, electric vehicle (EV) is using fuel cell as a prime source of energy because of its high promising performance and clean source of energy. However, due to low dynamic performance it alone cannot meet the fast changing load requirement during acceleration or sudden uphill, deceleration or sudden downhill. Therefore, in EV, main source is used in appropriate combination with auxiliary source. This article presents a comprehensive state-of-the-art of control strategies for maintaining constant DC bus voltage under transient load condition. It also presents a complete modeling by including boost converter modeling with main source and buck boost converter modeling with auxiliary source. Further, the dynamic evolution controller and Lyapunov-based control strategies for EV has been discussed with drive cycle.

Introduction

The conventional vehicles are mainly using petrol or diesel as a fuel which causes pollution and emission of green house gases. Pollution caused by vehicle emissions poses dangerous consequences to the human life and environment. So, it becomes the urgent need to think an alternate transportation medium such as electric vehicles (EVs) (Gao and Member, 2005). Now these days, EV is more efficient and promising perspective for the future generation because they have many advantages such as reduction of carbon emission, improved efficiency and performance (Chan et al., 2010). The traction motors used in EVs are mainly DC motors, induction motor, synchronous motor and switched reluctance motor. The decision of selection of traction depends on power density, efficiency, controllability, reliability, technological maturity, and cost (Vicatos and Tegopoulos, 2003; Yang et al., 2015; Zeraoulia, 2006).

Generally, EVs use two sources of energy namely, main source and auxiliary source. Main energy source is characterized with high energy density while auxiliary source with high power density. Main source provides continuous energy and whenever the load increases, the auxiliary source supplies the surplus power. Moreover, the auxiliary source stores the energy at the time of breaking termed as regenerative breaking which makes vehicles more efficient. The development of fuel cell technology and higher energy storage

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* Corresponding author. Tel.: +91 8171573929.
E-mail addresses: hitesh.sharma_mtee14@gla.ac.in (H. sharma), skmaurya@ieee.org (S.K. Maurya).

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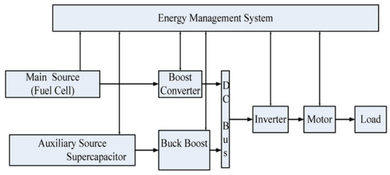

Figure 1 Power circuit of a typical electric vehicle.

enables its use in automotive application. Now these days, the fuel cell system is integrated to provide the load demand of vehicle with auxiliary source such as battery or ultra capacitor (Jacob, 2004; Khaligh and Li, 2010; Mehta and Cooper, 2003; Ortúzar et al., 2007; Young et al., 2011).

So far, various researchers have taken this problem of controlling main source and auxiliary source shown in Fig. 1 by using conventional linear control techniques. However, converter and fuel cell exhibits non-linear dynamics characteristics, then in such case, using linear controller can be used only around certain operating points. In this article, reviews of the dynamic evolution controller and Lyapunov-based control technique have been discussed.

System representation

Generally, auxiliary energy source is connected in parallel with main energy source through a suitable converter topology to the DC bus in EVs. The selection parameters of converter are mainly its compactness, flexibility, efficiency and reliability. This article considers boost converter with main energy source and buck boost converter with auxiliary energy source before connecting to the DC bus. The combined model of fuel cell and supercapacitor is shown in fig. 2.

Boost converter modeling

The main source does not allow reversible current, so a unidirectional converter is adapted. The converter is composed of high frequency inductor(L_1), a filtering capacitor(C_{dc}), a diode D_1, and a power electronics switch (s_1) mainly insulated gate bipolar transistor (IGBT) controlled by input signal (u_1) is used in this modeling. The input capacitor (C_{fc}) is used to protect fuel cell against overvoltage in high power demand (El Fadil et al., 2014; Todorovic and Palma, 2004). The output voltage and current of fuel cell are given in equation (1) and (2).

$$\dot{i}_{fcf} = -(1-u_1)\frac{v_{dc}}{L_1} - \frac{R_1}{L_1} i_{fcf} + \frac{v_{fc}}{L_1} \tag{1}$$

$$\dot{v}_{dc} = (1-u_1)\frac{i_{fcf}}{C_{dc}} - \frac{1}{C_{dc}} i_1 \tag{2}$$

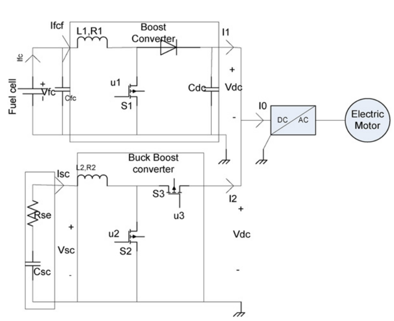

Figure 2 Combined model of fuel cell and super capacitor.

Buck boost converter modeling

The auxiliary source super capacitor or battery is connected to the DC bus by means of bidirectional converter called a buck boost converter. The buck boost converter allows the current to flow in both directions. The inductor is used for energy transfer and filtering. In this, two switches (s_2, s_3) are used which are driven by the binary input u_2 and u_3. The binary variable K will be boost converter if $K=0$ otherwise buck boost converter (El Fadil et al., 2014; Marchesoni and Vacca, 2007). The auxiliary current (i_{ax}) can be modeled as shown in equation (3).

$$\dot{i}_{ax} = -[K(1-u_2) + (1-K)u_3]\frac{v_{dc}}{L_2} - \frac{R_2}{L_2} i_{sc} + \frac{v_{sc}}{L_2} \tag{3}$$

Control strategies used in electric vehicle

In EV, the fuel cell and auxiliary sources are connected in three main topologies: FC and battery, FC and ultra capacitor, FC, battery and ultra capacitor. This article considers control strategies for primarily two main topologies which are widely used in EV. The control strategies are designed in such way that it will maintain DC bus voltage and provide current limit from auxiliary source on change in load. For this, the KCL is applied at DC bus connecting with auxiliary and main source. Further, combining the converter modeling equation with current set of bilinear switched model can be obtained. After converting into state model, the duty cycles μ_1, μ_{23} from boost converter and buck-boost converter, respectively, are given by equation (4). Where x_1, x_2 are average value of current from main source, auxiliary source and x_3 is DC bus voltage.

$$\mu_1 = 1 - \frac{L_1}{x_3}\{c_1 e_1 - e_3 + \frac{V_{fc} - R_1 x_1}{L_1} - i_{fcref}\} \tag{4a}$$

$$\mu_{23} = \frac{L_2}{x_3}\{c_2 e_2 + \frac{V_{sc} - R_2 x_2}{L_2} - i_{scref}\}. \tag{4b}$$

Dynamic evolution control

By dynamic evolution control, we force error state to zero as the time passes for reducing the error. So, the dynamic evolution controller includes an error function. Considering state space average model in boost mode (Samosir et al., 2010) has presented a dynamic evolution controller model for charging or discharging of auxiliary source. After including linear error voltage, the duty cycle (α) of boost converter can be given by equation (5).

$$\alpha = \frac{V_{ref} - V_{ax}}{v_0} + \frac{(mk-1)}{v_0} V_{err} + \frac{k}{v_0}\frac{dv_{err}}{dt} + \frac{L}{v_0}\frac{di_L}{dt} \tag{5}$$

Where V_{ref} is the reference voltage, V_{ax} is the auxiliary source voltage, v_0 is the output DC bus voltage, m is the rate of evolution. This control approach provides better control of DC bus voltage during transient.

This dynamic evolution controller is implemented in Matlab 2013a by taking ultra capacitor as auxiliary source. Fig. 3(a) shows the demanded power for certain periods. The power demand during starting is 500 W. The time period 0.4—0.6 s is the period of braking, and after that, the power demand is −500 W. Fig. 3(b) shows the output voltage for certain period. The output voltage during normal operating condition is 100 V. During the time period 0.4—0.6 s,

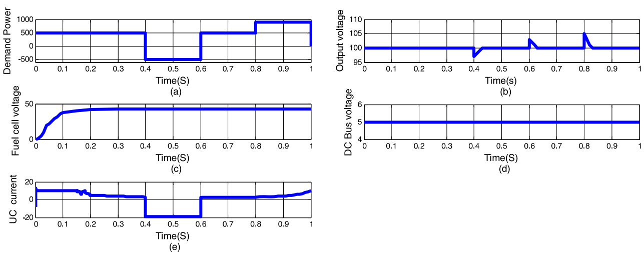

Figure 3 Simulation result (a) shows the demand power from load (b) shows the load voltage during transients (c) shows fuel cell voltage (d) shows DC bus voltage and (e) shows Ultra capacitor current.

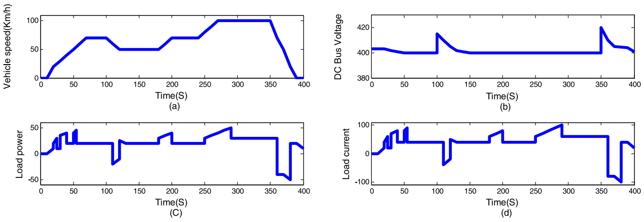

Figure 4 Simulation result (a) shows the speed of the vehicle (b) shows the DC bus voltage (c) shows load demand power and (d) shows load current.

when the regenerative braking is applied, the output voltage decreases for a short time period but during the time period 0.8—1 s, the speed increases due to which the output voltage is increased for a short time. Fig. 3(c) shows the fuel cell voltage. In this during start up, the fuel cell voltage is increased and then it will provide a continuous power to the load. Fig. 3(d) shows the DC bus voltage, which is constant for the whole time. Fig. 3(e) shows the ultra capacitor voltage in which during starting the voltage of ultra capacitor decreases with an interval of 0—0.4 s. At 0.4—0.6 s, regenerative braking is applied, so during this period, ultra capacitor stores the energy and when the load demand increases in the interval of 0.8—1 s, the ultra capacitor releases its energy to the load (Fig. 3).

Lyapunov-based control technique

The control objectives which are followed by this control technique are, maintaining DC bus voltage during change in load, track the auxiliary current to its reference value and maintaining stability of whole system. To maintain DC bus voltage, an error signal is generated from fuel cell current compared to its reference value. After getting an error, the control signal of boost converter is obtained as given in equation (4) (a) the objective forces the error to minimize, where μ_1 is the control signal of boost converter. The second control objective is to track the auxiliary current to its reference value; in this also error signal is generated. After getting an error signal, the control signal of buck boost converter is obtained as given in equation (4) (b) where μ_{23} is the control signal of buck-boost converter. The third control objective is to maintain the stability of the system. This can be carried out by control signal which stabilizes the whole system with state vectors, which shows that the closed loop system with state vectors is asymptotically stable (Fadil et al., 2012).

The Lyapunov-based control strategy is implemented in Matlab 2013a. In this, the speed of the vehicle changes with different intervals of time as shown in Fig. 4(a). Due to this, DC bus voltage changes as the vehicle speed changes as shown in Fig. 4(b). The load power and load current changes significantly as the vehicle speed changes as shown in Fig. 4(c) and Fig. 4(d).

Conclusion

This article presents a comprehensive review of the control techniques used for maintaining the DC bus voltage and charging and discharging of auxiliary source under transient condition of an EV. Further, the simulation results under transient condition for Lyapunov and dynamic evolution controller have been presented.

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